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1. REPORT DATE (DD-MM-YYYY) 12-03-1998	2. REPORT TYPE Paper	3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE

Service Life Prediction Technology Program

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER 1011
5e. TASK NUMBER 00NF
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)

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10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-PR-ED-TP-1998-061

12. DISTRIBUTION / AVAILABILITY STATEMENT

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20020115 063

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON James Fillerup
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	A		19b. TELEPHONE NUMBER (include area code) N/A

SERVICE LIFE PREDICTION TECHNOLOGY PROGRAM

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ABSTRACT

The Service Life Prediction Technology Program is part of the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program under the area of Strategic Sustainment. The overall goal of IHPRPT is to double the state-of-the-art national rocket propulsion capability by the year 2010. The primary objectives of the Service Life Prediction Technology program are to reduce the uncertainty in predicted stresses and strains, to reduce material failure characterization uncertainties, and to reduce aging model uncertainties. Emphasis of the program will be to: 1) investigate and implement nonlinear constitutive laws (including laboratory characterization methods); 2) to characterize and model chemical migration and reactions in aging propellants and bondlines; and 3) to investigate and establish nondestructive methods which can be used to characterize the in-situ propellant properties and property variations in solid propellant rocket motors.

INTRODUCTION

The Service Life Prediction Technology Program is a five year effort which is part of the overall Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program. This paper is not to address all aspects of IHPRPT, however, it is considered worth while that the reader understands how the Service Life Prediction Technology Program fits into the overall IHPRPT program matrix.

IHPRPT is the national rocket propulsion technology development and demonstration program to provide revolutionary advancements in rocket propulsion performance and operational capability. Its participants are the Department of Defense (DoD), NASA and the rocket propulsion manufacturing industry. IHPRPT seeks to insure a unity of goals for improved propulsion components and supporting systems. The overall goal of IHPRPT is to double the 1993 state-of-the-art national rocket propulsion capability by the year 2010.

Boost & Orbital Transfer	Spacecraft	Tactical
PROPELLANTS		
Advanced Solution Propellant Technology	Monopropellant Replacement for Hydrazine	Tactical Hybrid Rocket Engine Applied Technology
	Advanced Monopropellant Formulation Scale Up	
	Scale Up and Transition of Oxidizers and Fuels	
PROPELLANT MANAGEMENT DEVICES		
COMBUSTION & ENERGY CONVERSION		
	Light Weight Engine Nozzle	
CONTROLS		
TECHNOLOGY DEMONSTRATORS		
STRATEGIC SUSTAINMENT		
1.3 Boost Propellant		High Performance PBCS
Service Life Prediction		
NDE Data Processing Tech.		
Critical Defect Assessment Tech.		
MATERIALS		
Structural Ceramics for Rocket Engines		
Advanced plastic LH 2 Turbopump Housing		
Ceramics for Rocket Engines		

Figure 1. IHPRPT Program Matrix for FY98 and FY99

The IHPRPT program is organized into three mission application areas as shown in Figure 1: Boost/Orbital Transfer Propulsion, Spacecraft Propulsion and Tactical Propulsion.. The graphic overview depicts the mission application areas (columns). Under the mission application areas are five identical technology areas (shaded) plus Strategic Sustainment Technology under both the Boost/Orbital Transfer Propulsion and Tactical Propulsion. The five identical areas for each application area are Propellants, Propellant Management Devices, Combustion and Energy Conversion Devices, Controls, and Technology Demonstrators. The first four of these technology areas are consistent with recognized areas of specialized expertise. The fifth area covers a roll-up of the technologies into a demonstration of goal achievement. The area of Strategic Sustainment addresses new and existing technologies which might be incorporated into existing and future strategic missile systems to enhance their capability to sustain an operational system. A seventh area, entitled Materials, supports the other six technology areas.

Under the technology areas are listed the individual programs. These programs are part of the Program Research and Development Announcement (PRDA) for FY98 and FY99 contact awards. As mentioned, this paper will only address the Service Life Prediction Technology Program. Nevertheless, the other programs listed provide insight as to the overall development efforts of IHPRPT.

PROGRAM DEVELOPMENT

Program Objectives

In the 1997 Annual Report of the JANNAF Structural and Mechanical Behavior Subcommittee (S&MBS) it states:

> "Service life analysis and prediction techniques for solid rocket motors have developed in a somewhat haphazard and uncoordinated fashion, with methodologies being developed for specific system applications. Current methods of prediction service life needs to be better documented and a guideline is needed to help the engineer or scientist in choosing or developing service life programs for existing systems as well as for systems in the design stage. Confidence in service life prediction needs to be improved."

Based on the needs identified in the above statement, the goal of the Service Life Prediction Technology Program is to provide a guideline and develop confidence in service life prediction. As a result, the technical objectives for the program come directly from deficiencies identified by the JANNAF S&MBS from input from U.S. government agencies and industry.

As previously stated, the overall objectives are to develop methodologies that will reduce the level of uncertainty in predicting the service life of solid rocket motors. Specifically, these objectives are to reduce the uncertainty in predicting stresses and strains, to reduce material failure characterization uncertainties, and to reduce aging model uncertainties. The achievement of these objectives is to be demonstrated via test and analysis during this program. Emphasis of the program will be on the investigation and implementation of nonlinear constitutive laws (including laboratory characterization methods), procedures for extracting propellant grain material properties from data produced by nondestructive inspections of solid rocket motors, and modeling and characterization of chemical migration and reaction in the aging of rocket propellants and bondlines.

Program Selection Process

The PRDA process was used for selection of contract award. This is the process used for all of the IHPRPT programs listed in Figure 1. The PDRA process consists of an announcement released to the industry containing the program objectives and funding profile. In the PRDA, the industry is invited to develop programs which would meet the stated objectives. Abstracts from several companies are then

received and reviewed by an evaluation team consisting of individuals representing various government agencies and disciplines. This team evaluates the abstracts and downselects those abstracts which best meet the PRDA objectives.

Those companies whose abstracts were selected were then invited to give an oral proposal of their proposed program. The same team that evaluated the abstracts, also evaluated the oral proposal. All or part of the program presented could be selected for contract award. After ranking the oral presentations, a program is recommended for contract award. In the case of the Service Life Prediction Technology Program, the program submitted by Thiokol Corporation program was recommended for contract award.

PROGRAM SPECIFICS

Program Philosophy

The program philosophy is based on moving from an empirical approach to a mechanistic approach. In the past, aging and surveillance programs relied on empirical aging data to extrapolate to a service life prediction for a given rocket motor. This empirical approach is illustrated in Figure 2. The process involves gathering trend data. This typically involves accelerated aging data obtained by subjecting test specimens to elevated temperatures. These test specimens often include propellant/liner/insulation (P/L/I) carton specimens and/or analog motors. The data is then plotted and fitted to a curve. The curve is then extrapolated to predict the aging trends. Based on the aging trend and data scatter, a service life for the motor system is estimated. Generally, extrapolation past five years has not been widely accepted due to lack of confidence in the extrapolation past that period of time.

Figure 2. Empirical Approach

Figure 3. Years of Aging Surveillance is from Empirical to Mechanistic Approaches

To verify the service life prediction, at specified times (years later) verification tests are conducted to see how close real time aged data falls on the extrapolated curve. Test specimens for verification are usually obtained from costly dissection of real time aged analogs or full scale motors. At times, the empirical approach does not predict the aging trends well. Figure 3 is an example. As can be seen, there was a significant change in behavior past eight years which earlier extrapolation would not have predicted.
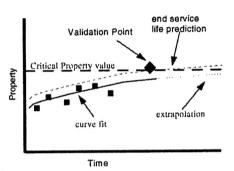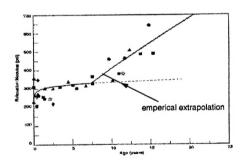
Proposed Mechanistic Approach. The proposed mechanistic approach to service life prediction is illustrated in Figure 4. It consist of five steps which are described below.

Step 1. Aging Mechanisms. The task here is to identify principal aging mechanisms occurring in a propellant and at the bondline, then to measure their diffusion/reaction parameters. Some of the aging mechanisms have already been determined for most propellant systems but the data base will be expanded through additional laboratory testing.
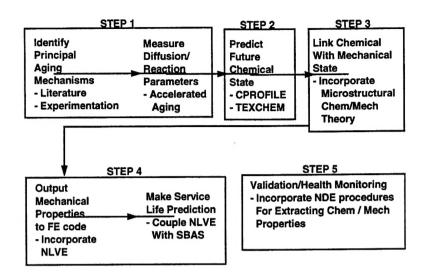
Figure 4. Proposed Mechanistic Approach

Step 2. Future Chemical State. This step is to predict the future chemical state analytically from chemical migration/reaction models developed in Step 1. Predictive analytical tools to be used include CPROFILE and TEXCHEM codes which were developed under previous Air Force contracts. CPROFILE is a 1D chemical kinetics/diffusion code capable of nearly all scenarios. This program will augment CPROFILE and make TEXCHEM into a 3D code with necessary enhancements such as a stiff equation solver to aid in computational convergence.
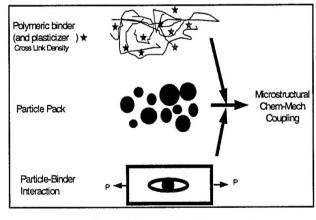

Figure 5. Microstructural Constructs

Step 3. Chemical Mechanical Link. The chemical-mechanical link is an indispensable feature of the mechanistic approach. The objective is to convert the predicted future chemical state of Step 2 to mechanical properties for use in structural analysis. This is to be accomplished by developing microstructural relationships between chemical states and nonlinear viscoelastic (NLVE) mechanical properties as a function of age. These microstructural models include the development of three constructs illustrated in Figure 5 namely, the polymer construct, the particle pack construct, and the particle-binder interaction construct.

Step 4. Structural Ballistic Analysis. In this step, the output mechanical properties generated in Step 3 are coupled with the structural models. As part of the program, improvements to the NLVE constitutive theory are planned. These improvements will be integrated into the Air Force's Structural-Ballistic Analysis System (SBAS). Hence, the structural integrity of an aged motor can be predicted.

Step 5. Non-Destructive Testing (NDE). The final step is the insurance policy which includes validation of analysis predictions and the health monitoring of solid rocket motors as they age. This is to be accomplisthed by developing techniques for extracting propellant grain material properties from data produced by nondestructive inspections of motors. If successful, a time-line of chemical and/or mechanical parameters can be tracked as a motor ages. This information can then be used to monitor individual motor degradation as well as verify service life predictions.

Program Tasks

In each of the five steps described above, new technologies must be implemented. As a result, the program has been divided into three major tasks with related subtasks. The three major tasks are: Task 1. Propellant/Bondline Constitutive Laws; Task 2. Propellant/Bondline Properties From NDE; and Task 3. Aging Mechanisms For Propellant/Bondlines. A flowchart of the program tasks is shown in Figure 6. Each of these tasks is discussed below.
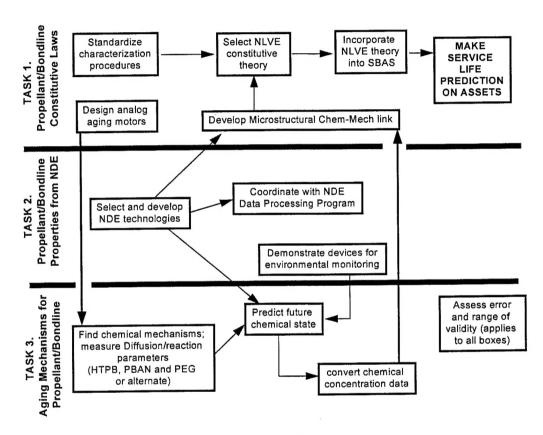

Figure 6. Program Flow Chart

Task 1. Propellant/Bondline Constitutive Laws. In Task 1 a nonlinear viscoelastic (NLVE) constitutive law will be selected and developed along with standardized characterization tests for the constitutive law. Included in the constitutive law will be microstructural chemical-mechanical models which link the material chemical state to mechanical states. Task 1 will also couple the NLVE structural analysis with ballistic analysis by incorporating it into the Air Force's Structural Ballistic Analysis System (SBAS). The design and manufacture of analog motors be used for the other tasks is also included.

Task 2. Propellant/Bondline Properties From NDE. The purpose of Task 2 is to develop NDE surveillance methods which can be used to extract motor material properties. This includes determining relationships between NDE and critical chemical, mechanical and physical properties for three propellant systems. The proposed propellant systems are HTBP, PBAN and PEG or an alternate. (More discussion on the propellant selection is given later in the Aging Testing Plan.) Initially, several NDE methods shall be investigated, but ultimately two will be selected for full development. Also included in this task is a study of off-the-shelf environmental monitoring devices which can be used to record temperature, relative humidity and shock loads of stored or deployed rocket motors.
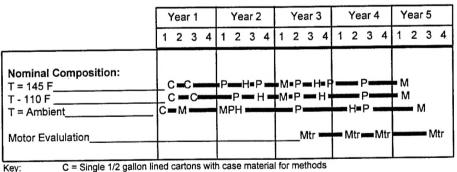
Task 3. Aging Mechanisms For Propellant/Bondlines. In this task, the principal aging mechanisms are determined and the requisite diffusion/reaction parameters are measured for the three propellant systems (HTBP, PBAN and PEG or an alternate). This task will also upgrade the existing Air Force computer code TEXCHEM which is a finite element diffusion/reaction code. The upgrades will include a 3D capability, a stiff equation solver and a data base for diffusion/reaction parameters in various materials. TEXCHEM will then be used to predict the future chemical state of propellants and bondlines. Algorithms shall also be developed and computer coded which shall convert chemical concentration data output from diffusion/reaction codes into a format usable by the microstuctural chemical-mechanical link of Task 1.

Finally an error assessment analysis will be conducted to assess the error and range of the validity for each of the tasks. This is a critical part of the program development since it will ultimately calculate the service life confidence level.

Aging Test Plan

As previoulsy stated, the proposed aging test plan encompasses three propellant systems. They include an HTPB base (Peacekeeper first stage), a PBAN base (Minuteman first stage) and PEG/BUNENA (a new propellant system proposed in the IHPRPT Strategic Sustainment Class 1.3 Boost Propellant Program). The final selection has not yet been established for there is some discussion to substitute the PEG/BUNENA for an existing system like a NEPE base (Trident II) or CTPB base (Minuteman second and third stages). To some extent, the final selection will depend on availability of full scale asset for demonstration of the new technologies. The final selection should be made by the end of March 1998.

The types of test samples used in the program are Propellant/ Liner/ Insulation /Case (P/L/I/C) cartons, P/L/I/C panels, analog motors and full-scale motor assets. Some of the specimens will be accelerated aged to force changes in the materials to establish various chemical and mechanical changes. Figure 7 shows the proposed aging test plan which is similar for each of the propellant systems to be considered. Those samples which undergo accelerated aging will be exposed to elevated temperatures of 110°F and 145°F.

	Year 1				Year 2				Year 3				Year 4				Year 5			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Nominal Composition: T = 145 F	C━C━━━━P━━H▪P━━M▪P━━H▪P━━━P━━━━M
T - 110 F	C ▪C━━━━P ━━ H ▪M▪P ━━ H ▪━━━P━━━M
T = Ambient	C▪M━━━MPH━━━━━━P━━━━━H▪P ━━━━ M
Motor Evalulation	Mtr ━━ Mtr━Mtr━━━ Mtr

Key: C = Single 1/2 gallon lined cartons with case material for methods
H = 3 1/2 gallon propellant cartons for NLVE analysis
M = Analog motors for NDE, NLVE and chemical analysis
P = P/L/I/C Panels for NDE and chemical analysis
Mtr = Asset motor evaluations

Figure 7. Aging Test Plan

In the first year, cartons will be dissected for testing to select chemical methods to measure age related changes and for the evaluation of the various NDE methods. In later years aged P/L/I/C panels will be dissected for testing to identify chemical aging mechanisms and to measure diffusion/reaction parameters for the TEXCHEM finite element code. These panels will also provide specimens for NDE evaluation and mechanical data for NLVE analysis.

Analog motors will also be included in the accelerated aging process along with the P/L/I/C panels. These 10.6" diameter, 26.9" long analog motors are an essential part of the validation test program. They will be used to evaluate NDE methods and verify TEXCHEM and NLVE analysis results. The motors will be equipped with environmental monitoring devices and embedded stress sensors along the bondline. From environmental gages, thermal, humidity and shock load data will be generated and used in both the chemical and structural analyses. The bondline stress gages will in turn provide data necessary to verify NLVE analyses. Some motors will be dissected to verify aging properties while others will be static test fired to be compared against SBAS analysis predictions.

Finally, service life predictions for a full scale asset will be undertaken. Currently, a Peacekeeper (PK-213) asset (donut slice) has been procured for this analysis. (Other assets have been identified and may also be included for more complete analysis as funding permits.) The testing of full scale assets is to demonstrate the NDE, chemical and modeling methodologies developed in this program.

Program Schedule

The program schedule is shown in Figure 8. It is divided into the three primary tasks with their corresponding subtasks. The numbers on the time-lines correspond to milestones listed below.
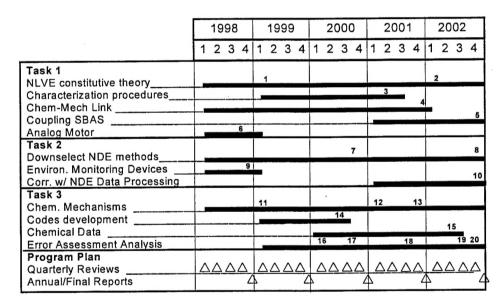
	1998	1999	2000	2001	2002
	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
Task 1					
NLVE constitutive theory____		1			2
Characterization procedures____				3	
Chem-Mech Link ____				4	
Coupling SBAS ____					5
Analog Motor ____	6				
Task 2			7		8
Downselect NDE methods____					
Environ. Monitoring Devices ____	9				10
Corr. w/ NDE Data Processing					
Task 3					
Chem. Mechanisms ____		11		12 13	
Codes development ____			14		15
Chemical Data ____					
Error Assessment Analysis			16 17	18	19 20
Program Plan					
Quarterly Reviews ____	△△ △△	△△ △△	△△ △△	△△ △△	△△ △△
Annual/Final Reports	△	△	△	△	△

Figure 8. Program Schedule

Milestones
1. Selection of most promising constitutive relation
2. Incorporation of selected constitutive theory into FE codes
3. Procedures for characterization tests that reduce failure envelope error
4. Full microstructural constitutive theory
5. SBAS codes, documentation and verification
6. Design and fabrication of analog motors
7. Selection of two NDE methods with AFRL consultation
8. Verification of two field-ready NDE techniques
9. Recommendation on devices for temperature, RH, shock
10. Compatible NDE data in format with NDE Data Processing Program
11. Principal chemical mechanisms for each of the 3 propellant systems
12. Diffusion/reaction parameters for each mechanism

13. Demonstrate technologies on real motor assets
14. Completed and verified TEXCHEM code
15. Analysis for converting chemical concentration data into structural data
16. Error assessment for chemical and micromechanical tests
17. Error assessment in constitutive characterization test
18. Error assessment in microstructural constitutive theory
19. Error assessment in field-ready NDE techniques
20. Error assessment for constitutive laws and SBAS

Program Deliverables

As the various technologies mature, they will be delivered to the Air Force and made available to the industry. For the most part, the data and technology development will be delivered in the form of annual reports, newly developed code and manuals. A description of the program deliverables is given below according to tasks.

Task 1. Propellant/Bond Constitutive Laws.

Under Task 1, a final NLVE subroutine for finite element analysis shall be delivered. Versions of this user subroutine shall be compatible with TEXPAC, and ABAQUS. As part of the NLVE development, the microstructural propellant constitutive theory shall be placed in a finite element code to link chemical state with the NLVE mechanical state. It will be tested by comparison with mechanical property tests on aging propellants. The microstructual theory shall include three microstructural constructs: the particle pack construct, the polymer construct, and the particle interaction construct.

In addition to the subroutine, recommended characterization test procedures shall be submitted from which the material model coefficients and failure properties can be derived. The recommended characterization will include test specimen configurations, testing procedures, and data reduction methods for input parameters to the new NLVE subroutine and for failure criteria. This includes procedures written for the microstructural tests needed for the microstructural propellant constitutive theory.

Along with the final version on the NLVE subroutine, the Structural-Ballistic Analysis System (SBAS) shall be upgraded with NLVE capability. SBAS is an Air Force structural ballistic code system which was developed to couple structural response to ballistic burnback analysis as illustrated in Figure 9. As shown in Figure 9, the focus of this program is to modify the structural component of the code. Note that the code system also has capability to include fracture analysis which will be upgraded during the Critical Defects Assessment Technology Program (refer to IHPRPT program matrix, Figure 1).
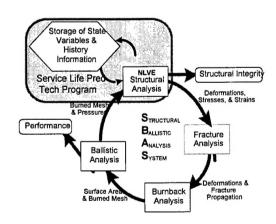

Figure 9. Incorporate NLVE Structural Upgrades into SBAS

At the end of the program a training session will be offered on the use the modified SBAS including user, training and theory documentation manuals. This training session will be open to the industry.

Annual reports and a final report at the end of the program will contain the verification test data and analysis. This will include the accelerated aging data base and analyses generated from cartons, test

panels and analog motors. Also the full-scale motor(s) service life analyses and the dissection data base will be included.

Task 2. Propellant/Bondline Properties From NDE

During the program the contractor shall assess NDE techniques that might be used to find chemical and mechanical properties associated with aging in sold rocket motor propellants and bondlines. By the end of the program, at least <u>two NDE technologies</u> shall be developed. The techniques chosen shall be applicable to three aging material systems (i.e. HTPB, PBAN and PEG or alternate). The theory and measurement procedures shall be documented and included in the annual and final reports. Also included in this task will be demonstrated environmental monitoring devices.

Task 3. Aging Mechanisms For Propellant/Bondlines.

In Task 3, experimental, analytical, and theoretical tools shall be developed that will be used in determining the actual chemical aging mechanisms in solid rocket motor propellants and propellant bondlines. In addition, error assessment and range of validity shall be quantified for all theories, models, experimental techniques, and computer codes either developed or used in the program. By the conclusion of this program, an <u>aging mechanisms data base for the three propellant systems</u> will be documented.

To utilize this data to predict future chemical states of a motor, <u>the TEXCHEM finite element code will be upgraded</u>. The upgrades will include a 3D capability (now only 1D and 2D), a stiff equation solver, and the data base for diffusion/reaction parameters. <u>Algorithms to convert chemical concentration data</u> will also be developed. These algorithms are used to convert chemical concentration output from diffusion/reaction codes into a format for the microstructural chemical to mechanical link.

Finally, <u>procedures for error assessment</u> and range of validity shall be quantified for each experimental technique, theoretical construct, model and computer code. The error assessment is a critical part of the program in predict the confidence level of service life predictions. Assessment of the sources of errors and the range of validity for each technology shall be included in bimonthly reports as the program progresses. In this way sources of error can be targeted and efforts focused to reduce the most prominent sources of error.

SUMMARY

In summary, the Service Life Prediction Technology Program intends to develop a mechanistic approach to service life prediction. The approach will be capable of predicting future chemical states of a propellant and associated bondlines and link the chemical state to mechanical properties for use in service life evaluation. In addition, the program intends to investigate and develop nondestructive evaluation methods for monitoring in-situ chemical/mechanical properties of aging motors. If successful, these technologies will be invaluable in assessing the health and reliability of exiting and future solid propellant rocket motors.